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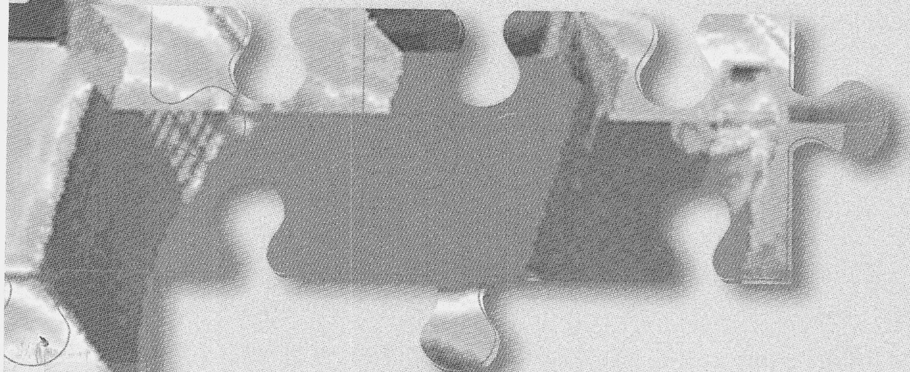
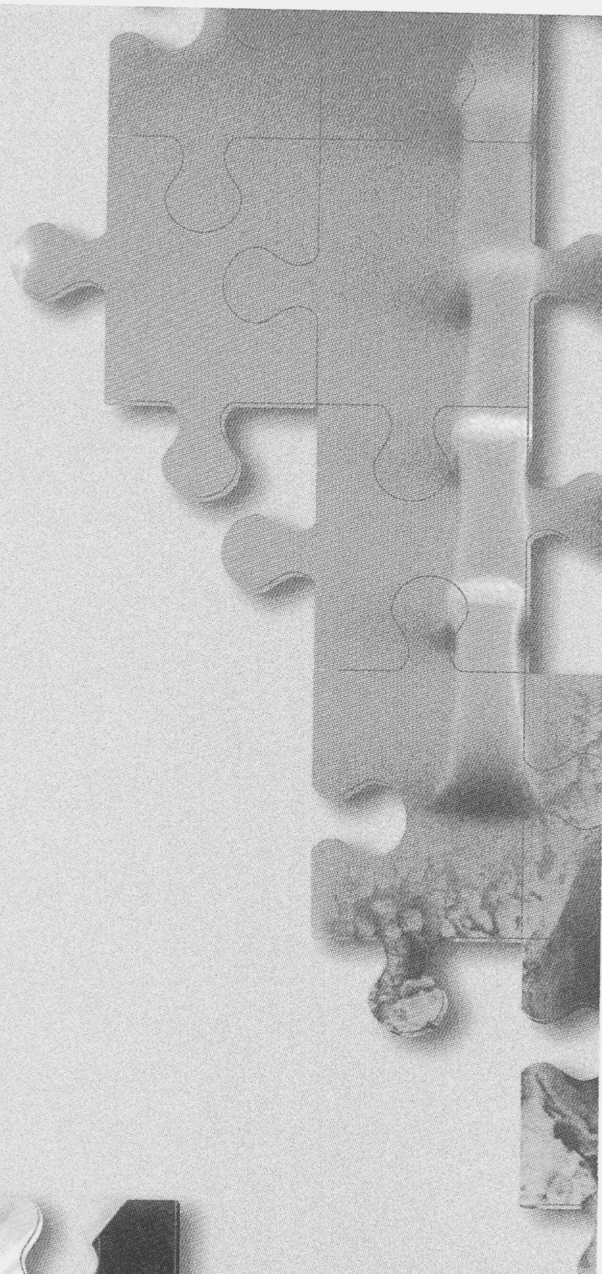
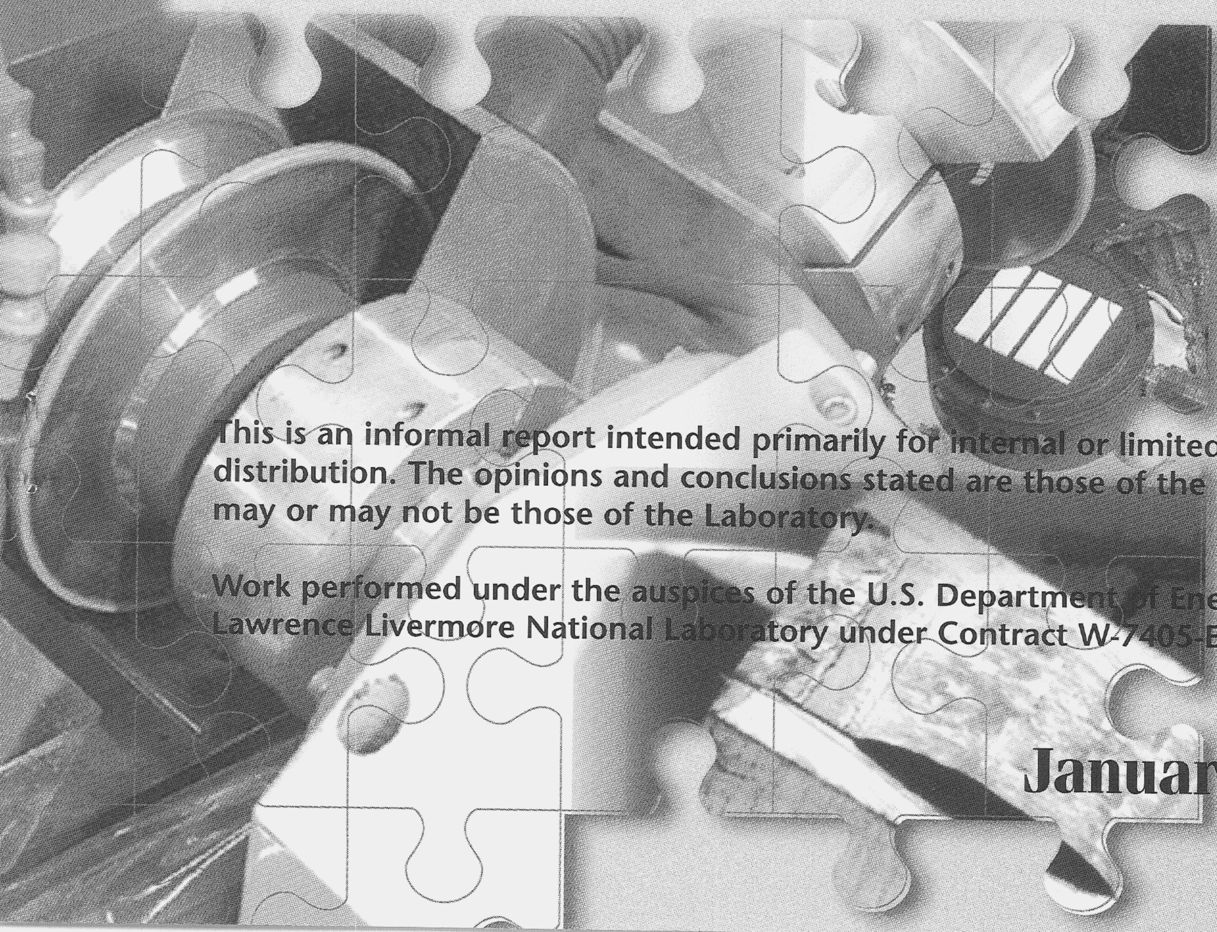




Optical Engineering

Theodore T. Saito,
Thrust Area Leader



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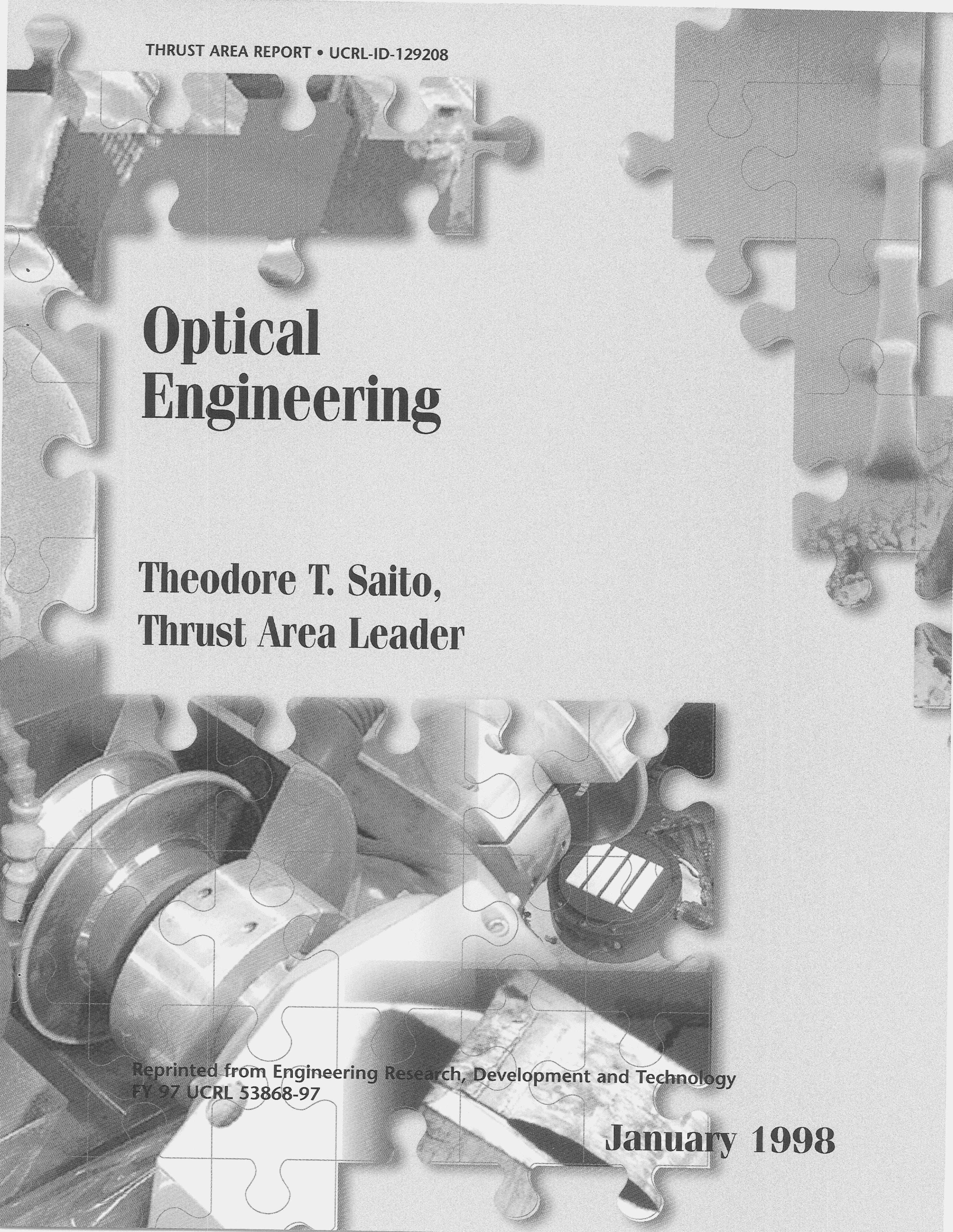

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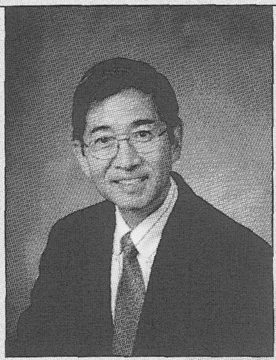

Theodore T. Saito, Thrust Area Leader

The Optical Engineering thrust area at Lawrence Livermore National Laboratory (LLNL) was created in the summer of 1996 with the following main objectives:

1) to foster and stimulate leading edge optical engineering research and efforts key to carrying out LLNL's mission and enabling major new programs;
2) to bring together LLNL's broad spectrum of high level optical engineering expertise to support its programs.

Optical engineering has become a pervasive and key discipline, with applications across an extremely wide range of technologies, spanning the initial conception through the engineering refinements to enhance revolutionary application. It overlaps other technologies and LLNL engineering thrust areas.

The table below is a small sampling of optical engineering's applications. A broader sampling of applications can be appreciated by reviewing the wide range of topics and papers presented by SPIE, the International Optical Engineering Society (http://www.spie.org/home.html).

LLNL's Laser Program is a major customer and supplier of optical engineering with applications that include the development of fast growth methods for KDP, the design and building of the $1.1 B National Ignition Facility (which will be the world's largest optical instrument), advanced microtechnology program, advanced image processing, isotope separation, and the development of diode-pumped solid-state lasers (DPSSLs) which have revolutionary futuristic potential.

The wide range of demanding needs for optical engineering in the Defense Sciences and Non-Proliferation directorates include electro-optics for advanced computing systems, electro-optical applications for advanced weapons systems, and advanced sensors for both above ground nuclear simulation experiments, and for detection of weapons proliferation activities.

Other optical engineering applications at LLNL are in the bioscience, energy, and manufacturing areas.

Optical Engineering Applications

Technology stage	Optical engineering examples
Initial Concept	• Optical design • Materials modeling—optical glass properties; laser media characteristics
Material Development	• Optical glass • Lasing media • Thin films • Deposition parameters • Optical fibers
Fabrication	• Optical polishing and precision machining • Chemical mechanical and ion beam removal and addition
Metrology	• Distance measurement • Shape (figure) and finish (roughness) measurements • Optical and spectroscopic properties • X-ray diagnostics
Special Applications	• Medical • Computational and communications

Optical Engineering

8

8. Optical Engineering

Precision Machining of Micro-Features in Structural Ceramics

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Precision machining has enjoyed an extensive history at Lawrence Livermore National Laboratory (LLNL) with one of its crown jewels being its diamond turning capabilities. In recent years, we have begun a required shift to precision grinding of materials for which diamond turning is not applicable, such as ceramics and other brittle materials. This project focuses on precision grinding of micro-features in structural ceramics such as Al_2O_3 and BeO. The approach uses a combination of experimental and analytical methods to investigate and develop precision grinding of brittle materials. Among the analytical developments are two computer grinding models to predict grinding wheel wear and sub-surface damage depths which result from the grinding operation. An extensive experimental process was developed to provide data in support of the analytical studies and simultaneously produce a method to fabricate BeO heat sink components important to LLNL programs.

Introduction

The objectives of this project are to define and extend our capability to perform precision grinding of brittle materials. Brittle materials are receiving increasing calls for use in high-performance components in a number of LLNL programs. One such material is beryllium oxide (BeO), which has outstanding heat transfer performance characteristics, yet is electrically insulating. BeO is the material of choice for a number of important LLNL and Department of Energy (DOE) programs.

The scope of the project includes modeling development, process analysis, and relevant experiments. The primary tasks for FY-97 included defining the current limits of brittle material precision grinding, establishing a modeling capability, and determining surface and sub-surface quality metrics to extend our precision grinding abilities.

Over the past decades, LLNL has established itself as a leader in precision engineering and lasers. Past engineering research and development have improved important material parameters impacting achievable accuracies and operational characteristics. Process development has included special development of precision fixturing, continuous lap polishing, and precision brittle material removal. Key weapons components and assemblies, as well as optical components (for example, for the Shiva and Nova lasers), have been fabricated.

Precision fabrication has been a key component in the Cooperative Research and Development Agreements (CRADAs) with a number of industrial partners, two of which provide the foundation for this project. The first was to develop 0.5-µm accuracy for a single-wheel slicing machine for electronic industry ceramic substrates (a factor of 8 in positioning accuracy).[1] The second was to demonstrate cost-effective ceramic removal rates while maintaining precise control of form geometry and the surface conditions that are required in ceramic engine parts.[2]

Progress

Modeling and Analysis

Both the precision and cost of a ground microfeature component are directly affected by the wear characteristics of the grinding wheel. Grinding wheels that appear "soft" in the grinding process wear excessively, resulting in loss of feature geometry control and expensive frequent wheel replacement. On the other hand, grinding wheels that appear too "hard" will maintain form, but due to insufficient breakdown of the bond to expose fresh abrasive, they will not cut freely and will burnish and damage the workpiece.

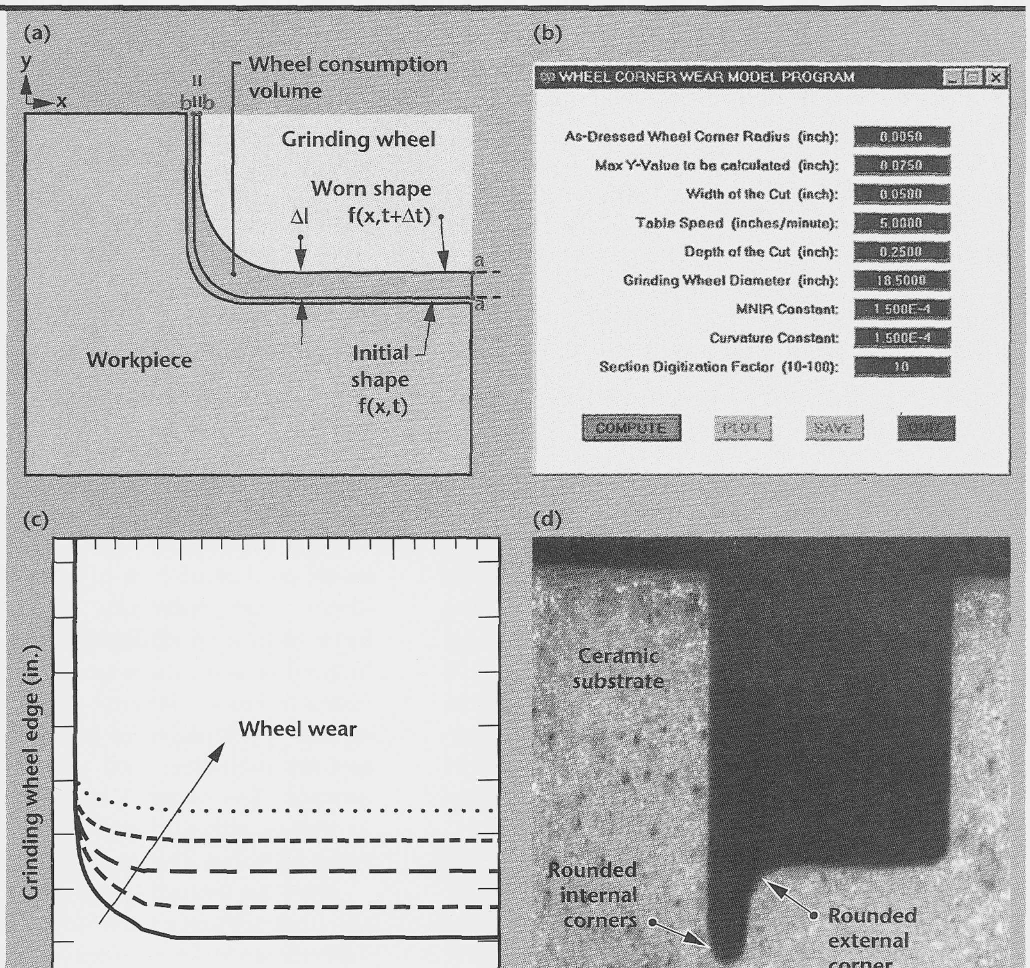
The need to better understand the wheel wear mechanism has prompted the development of a grinding wheel wear model.[3] This empirically-based model was developed to specifically investigate corner wear of a wheel during a grinding operation. Although this model was originally developed for abrasive wheels with much coarser abrasives than the grinding wheels used for these experiments, we feel this model can be further developed for our application.

Figure 1a shows a close-up schematic of a grinding wheel edge during the grinding of a workpiece. The wear model defines the initial shape of the grinding wheel edge using a specified number of points. The local wear at each point, Δl, may be expressed as

$$\Delta l = f\left(V_{nl}, \rho_l\right) \qquad \text{(Eq. 1)}$$

where V_{nl} is the normal in-feed velocity at each discretized point, and ρ_l is the local curvature at each discrete point.

Figure 1.
(a) Schematic of grinding wheel edge wear from time t, to time t + Δt; (b) grinding wheel wear model interface screen; (c) calculated wear profiles; and (d) groove image showing rounding of internal and external corners due to wheel wear.



The computer code marches iteratively through time and calculates the next profile, $f(x, t + \Delta t)$ based on V_{nl} and ρ_l. Empirically-based constants are instituted to obtain the local wear at each point along the profile and the local wear is expressed as

$$\Delta l = k_1 V_{nl}\left(1 + k_2 \rho_l\right) \quad \text{(Eq. 2)}$$

where k_1 is a maximum normal in-feed constant, and k_2 is a curvature constant.

With the grinding wheel corner profile determined as a function of time, the amount of volumetric wheel consumption is calculated by integrating the profiles at t and t + Δt. This is estimated as

$$\Delta V_{wheel} = \pi D_{nom}\left[\int_a^b f(z, t + \Delta t)dz - \int_a^b f(z, t)dz\right] \quad \text{(Eq. 3)}$$

where ΔV_{wheel} is the volumetric grinding wheel consumption during Δt, and D_{nom} is a nominal grinding wheel diameter for the corner section.

Figure 1b shows the user interface screen of our wear model; **Fig. 1c** shows sample calculated profiles of a grinding wheel corner vs time; and **Fig. 1d** shows a ground groove with non-sharp micro-features due to wheel wear.

Sub-Surface Damage Layer Analysis

Inherent in the vast majority of brittle material grinding processes is a resulting sub-surface damage (SSD) layer made up of a network of intergranular and intragranular cracks. Structural characteristics, such as breaking strength, were found to be a strong function of grinding-induced SSD.[2] Along with structural performance, the heat transfer capability of the ceramic components is often of key interest (particularly with high thermal conductivity materials such as BeO). Dr. B. Zhang (University of Connecticut)[4] has performed extensive experiments to examine the SSD layer (also referred to as the pulverized layer) introduced by a single-point fly cutter, which was used to simulate a single abrasive bound in a grinding wheel. **Figure 2** shows a schematic of a localized SSD layer induced by a single abrasive. The SSD layer consists of bulk material cracks and a pulverized area in which individual grains are crushed, significantly affecting its heat transfer capability.

Our investigation of the SSD includes the use of TEM analysis in which we examine cross-sections of ground specimens to determine the extent of the damaged layer. Using Zhang's grinding model (extrapolated to fine abrasive size grinding wheels), we predicted the SSD layer to be 10 μm thick or less, which, to first order, matches our experimental results. Material properties, wheel type, and grinding conditions all play important roles in creating this SSD layer.

Experimental Design

Precision grinding is a versatile, efficient, and robust process. Based on the methodology developed at LLNL, we use profiled super-abrasive, metal-bond diamond grinding wheels to precision grind ceramic substrates.[2]

Precision grinding, however, is not without its challenges and difficulties. Among these challenges are meeting geometric specifications and maintaining them through the course of a production run. Other issues include workpiece surface quality such as roughness and edge chipping, and the extent of SSD.

The experimental workpiece geometry selected was chosen for two main reasons: 1) it provides several of the most challenging and frequently required geometric features; and 2) it has a direct programmatic application. Among the geometric features to be studied are vertical wall straightness, minimum internal and external radii, surface roughness, and edge chipping.

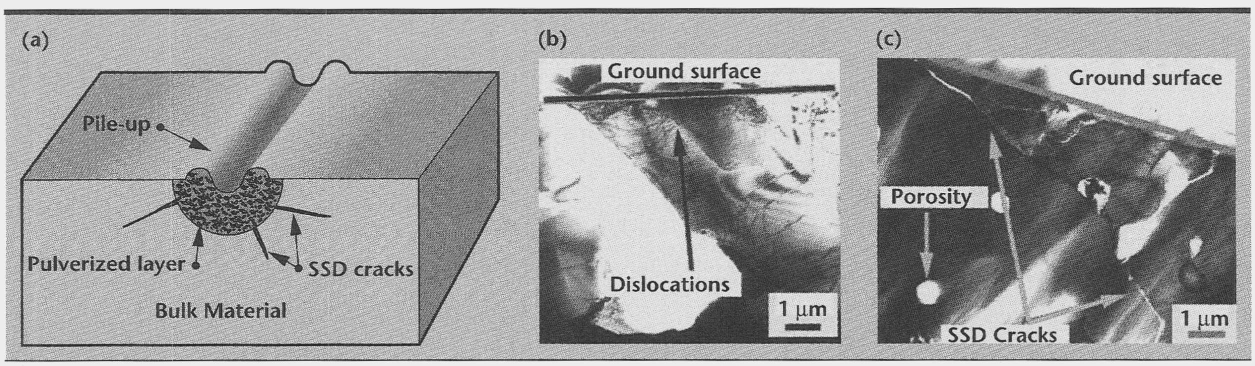


Figure 2. (a) Schematic of sub-surface damage layer as a result of material removal from an individual abrasive; (b) TEM image showing dislocation SSD (0.7 cm/min in-feed rate); and (c) TEM image showing SSD cracks (5.1 cm/min in-feed rate).

Figure 3a shows the experimental workpiece geometry used for this project. The dimensions of each individual groove are shown in the magnified view, and tolerances are nominally ± 1 µm. The pitch spacing between grooves is 1 mm ± 1 µm. Among the most critical features of the groove geometry are the sharpness of the external corner at the top of the 75-µm notch and the straightness of the left vertical wall.

The 75-µm notch (approximate thickness of a sheet of paper) at the bottom of the groove provides an excellent opportunity to investigate limitations of both internal and external corner minimum radii. **Figure 3b** shows a schematic of a double-profiled grinding wheel process and the wheel's progression through the workpiece. The right hand profile removes a majority of the groove, grinds the bottom notch and removes a small amount from the top surface for groove depth control. As the wheel progresses to the next grooves, the left wheel profile removes the remainder of the groove material and generates a sharp corner at the top of the 75-µm notch.

Figure 4a is a schematic showing the layout of the machine tool used for this project. A rotating EDM graphite electrode is profiled using a single-point tool or a grinding wheel. The electrode is used to EDM-true and profile the metal-bonded super-

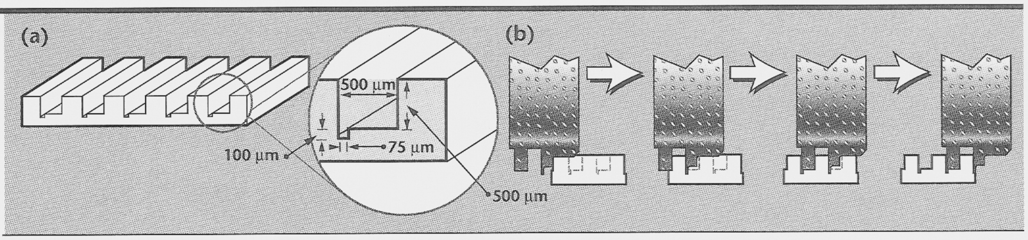


Figure 3.
(a) Experimental workpiece geometry; and (b) progressive grinding wheel procedure using a double-profiled grinding wheel.

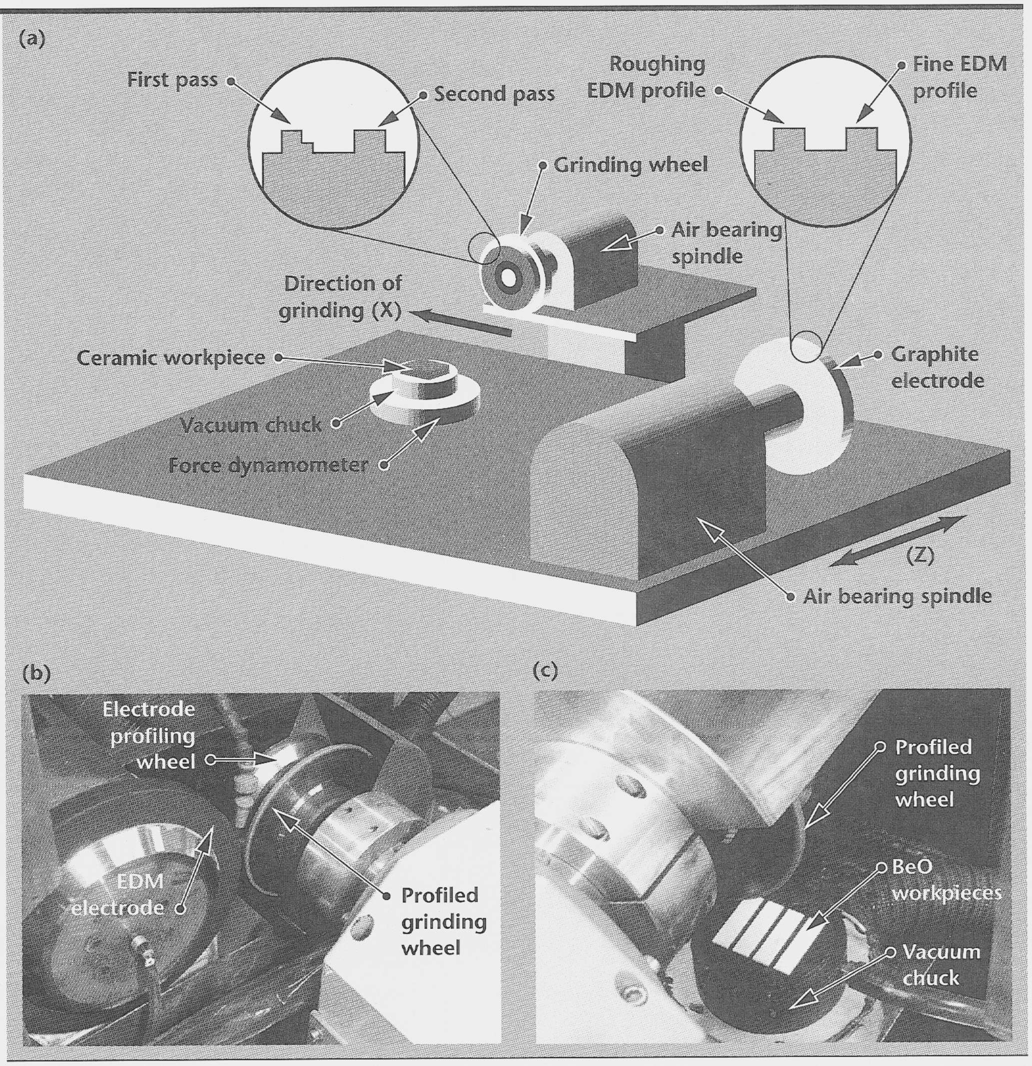


Figure 4.
(a) Grinding machine schematic; (b) EDM profiling and truing a metal-bond grinding wheel; and (c) profiled grinding wheel approaching four BeO workpieces.

abrasive grinding wheel, complete with the two profiles and 75-mm notch feature.

Truing of the grinding wheel is vital to reduce synchronous motion errors, which result in feature degradation and limit the minimum groove width. Once the grinding wheel has been profiled and trued, it is used to creep-feed grind the micro-features in the ceramic workpieces. This method can produce micro-features to small tolerances and, with the appropriate machine design and process, can be a low-cost method for manufacturing micro-features such as grooves.

Figures 4b and **c** are photographs of the grinding work zone of the machine tool used in the project. The machine is a converted T-base diamond turning lathe, with a temperature-controlled oil casing and distance-measuring laser interferometers that provide position resolution of less than 0.1 µm. This machine has been qualified for BeO machining.[5]

Figure 5a shows a completed BeO workpiece (1 cm × 4 cm × 0.2 cm) with 40 precision ground grooves. The table shown in **Fig. 5b** is a list of the typical process parameters and specifications.

Future Work

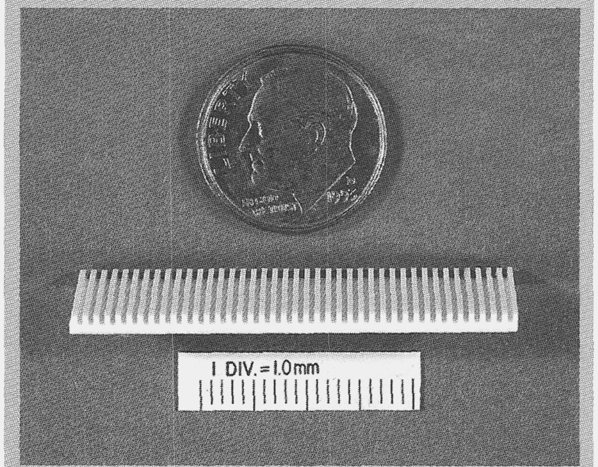
The future work associated with this project will continue to advance the analytical and experimental aspects of this technology. We will extend our analytical capabilities with continued collaboration with the University of Connecticut to develop applicable grinding models for super-abrasive, precision grinding of ceramics. This will include both grinding wheel wear and SSD modeling and developing experimental methods to corroborate them.

The experimental portion includes reducing the attainable micro-feature size and improving the cost-effectiveness and robustness of the process. Advancing the *in-situ* gaging process to quickly determine the compliance with the required specifications will add flexibility and lead to a more production-oriented process.

This project benefits several core competencies. The precision engineering and manufacturing area will benefit from the extension of achieving 1- to 2-µm feature accuracies in brittle materials. This work is a natural extension of the CRADA work with Cummins Engine Co. and Industrial Tools, Inc. (ITI).

The ITI CRADA demonstrated sub-µm accuracies of less complicated features in a two-phase ceramic, which is easier to cut than BeO. Also the maintenance of the 1- to 2-µm accuracies of period and 2-mrad vertical wall angle for this project is very demanding. We will gain better understanding of the degradation in the slicing process with regard to repeatably maintaining the 1- to 2-µm tolerances. These techniques will have benefit for other microelectronic applications requiring similar demanding tolerances.

(a)



(b)

Parameter	Description
Grinding wheel	SD1000, N100 M, 18 cm Ø
Workpiece	BeO
EDM electrode	Poco Graphite (1 µm grain size)
Wheel speed	105 m/s
Feed rate	7.5 cm/min

Figure 5. (a) BeO slotted component used for the experimental portion of this project; and (b) typical grinding parameters and specifications.

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